Pulsed Magnetic Field Measurements Using Faraday Rotation Diagnostics

Brent McHale
(925) 422-8730
mchale3@llnl.gov

It is often necessary to measure extremely large pulsed electric currents when conducting pulsed power, explosively driven pulsed power, or controlled fusion experiments. There are a limited number of diagnostics that can be used to accurately measure currents at these levels. The most common are inductive field sensors that are susceptible to undesirable field coupling, and electromagnetic interference (EMI).

Faraday Rotation Diagnostics (FRD) relies instead on magneto-optical phenomena: the plane of polarization of light passing through magnetized media is rotated as it passes through the media. The degree of rotation is directly proportional to the magnetic field strength and the distance over which the magneto-optical interaction occur. By using optical fiber that is wrapped an integer number of times around current-carrying conductors, symmetry in Ampere's law is exploited, and the induced optical rotation can be related directly to the current flowing through the conductor.

A FRD of this type has been installed in the LLNL Pulsed Power Laboratory and used on a number of high interest experiments, including the Fixed Hybrid Armature (FHA) experiment, the ALE3D Coaxial Load Validation experiment, and the Magnetically Insulated Sulfur-Hexafluoride Transmission Line (MIST) experiment.

Project Goals

The goal of this project is to acquire local expertise in FRDs, and to assess and identify potential improvements to the diagnostic. This year, we had several technical milestones for diagnostic improvement, including migration to a lower wavelength of operation for improved diagnostic sensitivity, improved bulk-optics polarization analysis hardware, and demonstration of proof-of-concept of an all-fiber polarization analysis scheme.

Relevance to LLNL Mission

FRD sensors have excellent linearity and bandwidth characteristics, and are optically isolated and largely immune to EMI. These qualities make FRDs particularly well suited for application in

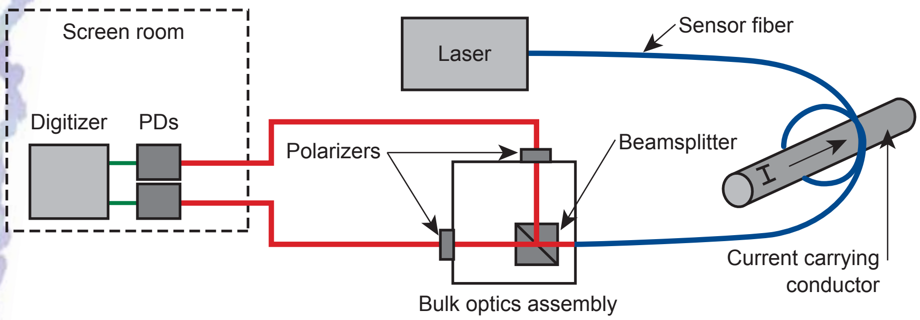

Figure 1. Block diagram of FRD system.

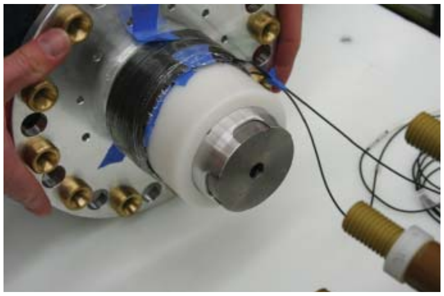

Figure 2. FRD sensor fiber installed on the ALE3D coaxial load test bed.

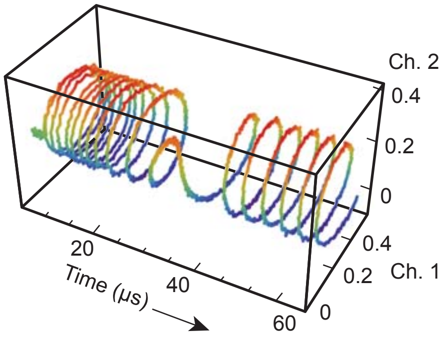

Figure 3. Raw FRD data from an FHA experiment. The pitch and handedness of the helix determines the sign and the rate of change of current. Peak current occurs at the reversal in helix direction near the middle of the figure.

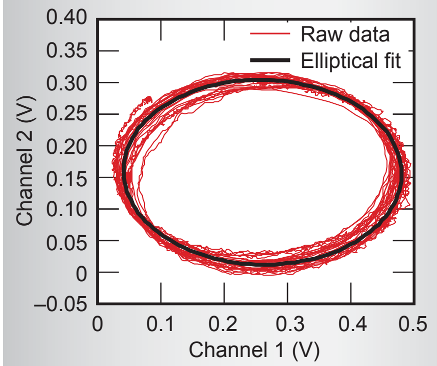

Figure 4. Projection of the helix in Fig. 3 onto *x-y* plane, and least-squares fit ellipse. Helix data is transformed using conic parameters of fit, and rotation deduced from fit. The resulting current waveform is shown in Fig. 5.

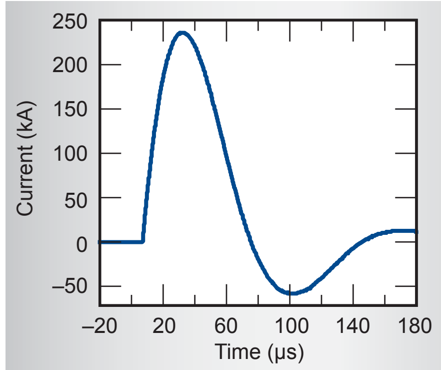

Figure 5. Current waveform computed from applying conic parameters in Fig. 4 elliptical fit to helical data in Fig. 3.

experiments that involve large quantities of guided or radiated electromagnetic energy. Since failure modes of FRDs differ from those of conventional inductive field sensors, FRDs offer a level of data redundancy for high-value single-shot experiments that is not easily achievable otherwise. Numerous programs at LLNL stand to benefit from this expertise, including explosive pulsed power for high-energy-density physics experiments, EM launcher experiments for military applications, and operations at NIF.

FY2008 Accomplishments and Results

A graphical depiction of the FRD implemented at LLNL is shown in Fig. 1. A 635-nm diode laser launches a few mW of linearly polarized light at a FRD sensor fiber, which is a twisted single-mode fiber installed in the experimental test bed (Fig. 2). The magnetic field in the vicinity of the sensor fiber induces Faraday rotation of the linearly polarized light. The rotating signal is coupled into a bulk optics assembly that splits the beam via a non-polarizing beam splitter and passes each beam through polarizers that are at a known relative angle. Both signals are then coupled through multi-mode fiber onto photodetectors and a digitizer in the screen room.

We have implemented the FRD on twenty-one shots across three experimental test beds with 100% data return. We have created a novel method of analyzing the data that is accurate and expeditious. A typical set of raw data is shown in Fig. 3; the helix shown is projected against the x-y axes where elliptical fit parameters are determined (Fig. 4). The elliptical fit parameters are applied to the helical data and rotation and current are computed. The results are shown in Fig. 5.

We have successfully migrated to a 635-nm system and have a proof-of-concept for an all-fiber polarization analysis scheme.

Related References

1. Rose, A. H., S. M. Etzel, and C. M. Wang, "Verdet Constant Dispersion in Annealed Optical Fiber Current Sensors," *J. Lightwave Technology*, **15**, pp. 803–807, May 1997.
2. Day, G. W., and A. H. Rose, "Faraday Effect Sensors: The State of the Art," *Proc. SPIE*, **985**, pp. 138–150, September 1988.
3. Bland, S. N., D. J. Ampleford, S. C. Bott, A. Guite, G. N. Hall, S. M. Hardy, S. V. Lebedev, P. Shardlow, A. Harvey-Thompson, F. Suzuki, and K. H. Kwek, "Use of Faraday Probing to Estimate Current Distribution in Wire Array Z Pinches," *Rev. Sci. Instrum.*, **77**, 10E315, 2006.

FY2009 Proposed Work

The primary focus of FY2009 will be to migrate from fiber-based sensors to highly sensitive glass probes that will provide magnetic field measurements at a point rather than integrated around a loop. We will continue to acquire expertise in ancillary aspects of FRD implementation such as sensor fabrication, modeling, and data analysis that permits improvement of the precision and accuracy of the diagnostic.